Disruption-Tolerant Wireless Sensor Networking for Biomedical Monitoring in Outdoor Conditions

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ABSTRACT

Off-the-shelf wireless sensing devices open up interesting perspectives for biomedical monitoring. Yet because of their limited processing and transmission capacities most applications considered to date imply either indoor real-time data streaming, or ambulatory data recording. In this paper we investigate the possibility of using disruption-tolerant wireless sensors to monitor the biomedical parameters of athletes during outdoor sports events. We focus on a scenario we believe to be a most challenging one: the ECG monitoring of runners during a marathon race, using off-the shelf sensing devices and a limited number of base stations deployed along the marathon route. Preliminary experiments conducted during an intra-campus sports event show that such a scenario is indeed viable, although special attention must be paid to supporting episodic, low-rate transmissions between sensors carried by runners and road-side base stations.

Categories and Subject Descriptors

J.3 [**Computer Applications**]: Life and Medical Sciences—*Health*; C.2.1 [**Computer Systems Organization**]: Computer-Communication Networks—*Wireless Communication*

Keywords

wireless networking, delay/disruption-tolerant networking, sensor networking, biomedical monitoring

1. INTRODUCTION

The concept of Wireless Biomedical Sensor Network (WBSN) opens up new opportunities for biomedical monitoring, such as the long-term, continuous monitoring of patients in a clinical environment or at home [1, 9].

In a typical deployment scenario, one or several battery-powered wireless sensors are attached to a patient, and a wireless base station is installed in this patient's surroundings. This base station can either store the data received from the sensors, or it can forward these data directly to a remote site, such as a physician's desktop computer or a hospital's monitoring center. In any case, since the sensors are wireless the patient can move freely around the base station, while an endless stream of data flows from the sensors he/she is carrying to the base station. This freedom of movement is however limited by the short transmission range of the wireless sensors. Indeed, most sensors include low-power radio transceivers (such as IEEE 802.15.4/ZigBee transceivers or, less frequently, IEEE 802.15.1/Bluetooth transceivers), with which actual transmission ranges are usually between a few meters (indoor) and up to a hundred meters (outdoor).

In traditional scenarios involving wireless biomedical sensors and a base station, it is commonly assumed that the transmission link between sensor and base station is continuously available and reliable. Transmission protocols can actually tolerate transient link disruptions without data loss, but the general assumption is that frequent, long-term disruptions should never occur while a patient's health status is being monitored. Such an assumption holds when a patient does not move much around the base station, as is the case in a hospital environment or at home. Yet there are other circumstances when the connectivity between sensor and base station can be seriously disrupted by the patient's mobility.

In this paper we investigate the possibility of using off-the-shelf wireless sensors to monitor the health of highly-mobile people in outdoor conditions. Our main motivation is to confront the possibilities offered by currently available sensors with the requirements of a demanding biomedical application, in order to assess if such an application can indeed be implemented using existing devices and technologies. To achieve this goal we focus on a scenario we consider as a most challenging one: monitoring the cardiac activity of runners during a marathon race. The underlying idea is that if biomedical monitoring can be performed in such a challenging scenario, then similar solutions can also be designed and implemented for less constrained situations.

The remainder of this paper is organized as follows. The marathon scenario we consider is described in Section 2, and Section 3 provides an overview of the sensors we plan to use in this scenario. In Section 5 we report on field trials we conducted during an intra-campus sports event in order to check the feasibility of ECG monitoring of runners. This section presents the conditions for the field trials. Lessons learned on that occasion are discussed in Section 6, as well as ongoing work. In Section 7 we conclude this paper, observing that monitoring the ECG activity of athletes in out-

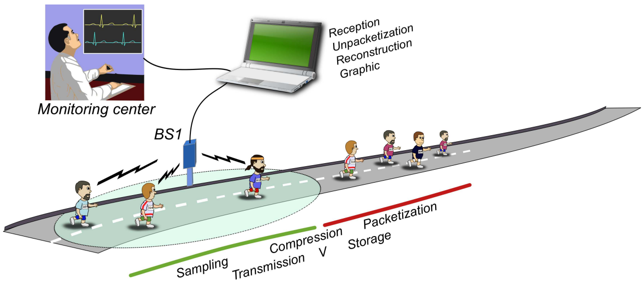

Figure 1: Illustration of disruption-tolerant ECG monitoring of marathon runners

door conditions is indeed feasible, but that this application is hampered by the low computation power offered by SHIMMER sensors and short range and low bitrate of 802.15.4 transmissions.

2. DESCRIPTION OF THE MARATHON SCENARIO

The scenario we consider as a test case is defined as follows: we assume the cardiac activity of athletes must be monitored using off-the-shelf sensors featuring an ECG sensing element during a marathon race. This particular scenario was selected because runners must cover a long distance during a marathon, and that distance clearly exceeds the limited radio range of the low-power IEEE 802.15.4 radio transceivers available on most current sensor platforms. Besides, since runners in a marathon all follow exactly the same route, a number of base stations can be deployed along that route (see Figure 1).

A base station (BS) is typically composed of a processing unit —for example a laptop— featuring an 802.15.4 interface, and at least one wired or wireless interface for long-distance transmissions (typically an access to the Internet). The 802.15.4 interface is used to receive data from the sensors carried by marathon runners, and the long-range interface is used to forward these data to a remote site (for example the closest medical aid station, or a physician's desktop, laptop, or smartphone). Data received from the sensors can be processed locally on the BS before being forwarded to the monitoring site, although that is not a requirement.

We conducted a series of preliminary tests in outdoor conditions in order to measure the radio range that can be observed between 802.15.4 transceivers operating at full power. We measured that this range can reach up to 50 meters in ideal conditions, but that an average value is closer to 30 meters. A BS deployed along a marathon route would thus cover about 60 meters of that route, and about 700 base stations would be required to ensure a full coverage of the 42.2 km route.

Since deploying that many base stations is hardly an option for organizational and financial reasons, our approach is based on the assumption that only a sparse coverage of the route can be ensured, using a reasonable number of base stations. A disruption-tolerant solution for data gathering must therefore be implemented, using the store-carry-and-forward principle. This principle is the foundation of *Disruption-Tolerant Networking (DTN)*: a mobile node that is temporarily disconnected from the rest of the network can *store* data (or messages) in a local cache, *carry* these data for a while, and *forward* them later when circumstances permit [4]. In our scenario, the ECG sensor carried by a runner captures data continuously and stores these data locally. Whenever the runner passes by a BS, a transient radio contact occurs between the sensor and that BS. This contact is exploited by the sensor to upload data to the BS, which in turn can relay these data to the monitoring center (see Fig. 1). The distance between successive base stations and the speed of the runner determine how often "fresh" data can be sent to the monitoring center. According to cardiologists we consulted, a physician monitoring the cardiac activity of marathon runners should receive updated data for each runner at least every 5 to 10 minutes, in order to be able to detect arrhythmias and prevent incidents. Considering the pace of an average runner this implies that base stations should be placed about 1 to 2 km apart.

To the best of our knowledge, utilization of the store-carry-and-forward approach to collect biomedical data in outdoor conditions has not been investigated much so far, although disruption-tolerant solutions for *non-biomedical* sensor-based applications have already been proposed in the literature [13, 8, 12].

3. OVERVIEW OF OFF-THE-SHELF WIRELESS SENSOR DEVICES

As a general rule a typical sensor node —or *mote*— is composed of a micro-controller or full-featured CPU, one or several transceiver modules, internal and/or external memory, a power source, and one or more sensing elements. In our project we use SHIMMER platforms as biomedical sensors and TELOS-B platforms as the radio units of our base stations (see Fig. 2).

Both kinds of platforms feature an 8 MHz TI MSP430 micro-controller with 10kB RAM, 16 kB EEPROM, 48 kB flash memory (for program code), and 1 MB external flash memory (for data logging). The radio module is based on an IEEE 802.15.4/ZigBee compliant CC2420 transceiver, which operates in the 2.4 GHz ISM band and allows data rates up to 250 kbps. Data acquisition is performed on up to 8 channels through a 12-bit AD converter. Programming and data collection can be performed either via a radio link or via a built-in USB interface.

Crossbow's TELOS-B "mote" platform includes sensing elements for light (visible and IR) and for humidity. Additional sensing elements can be connected to the platform through a USART (UART/SPI/I2C and DMA) and digital I/O bus. Power is provided either by 2 AA batteries or by the USB interface.

The SHIMMER platform is mostly dedicated to recording and transmitting physiological and kinematic data [3]: several kinds of expansion modules are available, including physiological sensors such as ECG (electrocardiography), EMG (electromyography) or GSR (galvanic skin response) sensors, as well as kinematic sensors for 3-axis angular rate sensing and 3-axis low field magnetic sensing.

The ECG expansion module of the SHIMMER platform provides RA-LL (Right Arm - Left Leg) and LA-LL (Left Arm - Left Leg) input leads. The RA-LA (Right Arm - Left Arm) lead can then be calculated based on the first two leads. Sampling is performed on each RA-LL and LA-LL channel by 12-bit A/D converters, and the sampling fre-

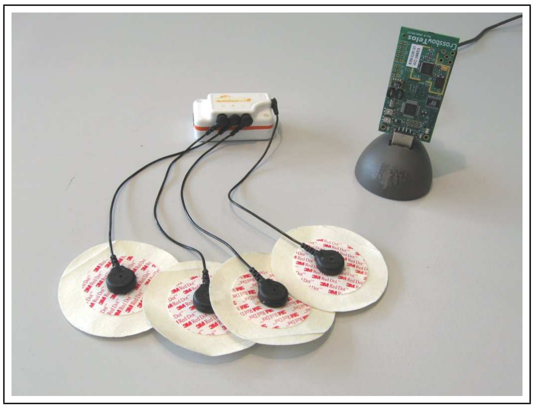

Figure 2: The two kinds of motes used in this project. The SHIMMER sensor (left) with its ECG expansion module and electrodes will be carried by runners, and the TELOS-B mote (right) will serve as the radio transceiver of a base station

quency can be adjusted between 200 Hz and 1 kHz. ECG sampling on two channels therefore produces a continuous stream of data, at a rate that can be adjusted between 4.8 kbps (for 200 Hz sampling) and 24 kbps (for 1 kHz sampling). A 2 GB micro-SD card provides storage capacity for data logging, and the platform is powered by an integrated 250 mAh Li-Ion battery. Besides the ZigBee-compliant CC2420 transceiver, the SHIMMER platform also includes a WML-C46A class 2 Bluetooth transceiver.

Like many other sensor platforms the TELOS-B and SHIMMER platforms are driven by TinyOS, a free and open-source component-based operating system targeting wireless sensor networking [10]. TinyOS applications are built in nesC (a dialect of the C language optimized for low memory consumption) out of event-based software components, some of which present hardware abstractions and others higher-level abstractions such as packet communication, routing, sensing, actuation and storage.

4. REQUIREMENTS AND CONSTRAINTS

The implementation of our disruption-tolerant transmission scenario for marathon monitoring might seem to be quite straightforward. Yet the problem is that ECG monitoring is a rather demanding application, whereas radio transmissions based on the IEEE 802.15.4 standard can only be achieved on short distances, and with low data rates. The question is therefore to determine if the requirements of ECG monitoring can be balanced with the constraints of episodic, low-rate, and short-range transmissions.

In order to answer this question it is necessary to evaluate the exact requirements of ECG monitoring, as well as the possibilities offered by SHIMMER and TELOS-B platforms for outdoor data transmission.

4.1 Requirements of ECG monitoring

ECG monitoring is usually performed with a 500 Hz sampling frequency, and the SHIMMER platform's A/D converters have a 12-bit resolution. In such conditions the bitrate of the data stream produced by the platform's 2-channel ECG module is 12 kbps. If needed several options can be considered in order to reduce this figure:

- Using lower sampling frequency and resolution: a 200 Hz sampling with 8-bit samples (on each channel) would for example produce a 3.2 kbps data stream. Such parameters may of course alter the quality of the ECG data stream, but signal reconstruction techniques can be used on the receiver side in order to compensate for this low quality [14].

- Compressing ECG data before storage and transmission: an important constraint here is to implement an algorithm that does not exceed the computation power of the SHIMMER platform's micro-controller, such as that proposed in [6].

- Processing ECG data on the SHIMMER platform, and transmitting reports and alerts rather than the whole data stream: a recognition module for cardiac arrhythmia is proposed in [11], and delineation algorithms for the automatic detection of the major ECG characteristic waves are described in [2]. The algorithms proposed in both papers have a low computational complexity, so they can run on resource-constrained platforms such as the SHIMMER platform.

4.2 Constraints presented by sensor platforms

The SHIMMER and TELOS-B platforms we use in this project both include IEEE 802.15.4 transceivers that allow a 250 kbps transfer rate. This transfer rate is actually the signaling rate that can be achieved on the radio channel. The actual transfer rate available at application level is of course significantly lower than that signaling rate.

In order to clarify the real potential of 802.15.4-enabled sensor platforms for data transmissions in our marathon scenario, we conducted a series of preliminary field experiments:

- Power consumption: we observed that a SHIMMER sensor with an ECG expansion module car run for almost 10 hours on its built-in battery (while storing ECG data on the micro-SD card and sending these data continuously on the wireless channel).

- Radio range: as mentioned before the radio range between SHIMMER and TELOS-B platforms is around 30 meters (on average) for outdoor transmissions, although transmissions on up to 50 meters can sometimes be observed.

- Transmission bitrate: the achievable transfer rate between sensor and BS cannot exceed 50 kbps.

The transmission bitrate mentioned above is surprisingly low compared to the standard's 250 kbps signaling rate. Yet this is the maximal bitrate we observed, and this result is actually consistent with other results mentioned in the literature [5] and in the TinyOS forum. Indeed it appears that the architecture of the SHIMMER and TELOS-B platforms both present a transmission bottleneck, which lies in the connection between the micro-controller and radio transceiver. Although the CC2420 radio transceiver can send and receive frames at 250 kbps on the radio channel, these frames can only be transferred to or from the micro-controller at a very limited rate. This is an important disadvantage for our marathon scenario, which requires that a single base station be able to receive data streams from several ECG sensors in the same timespan.

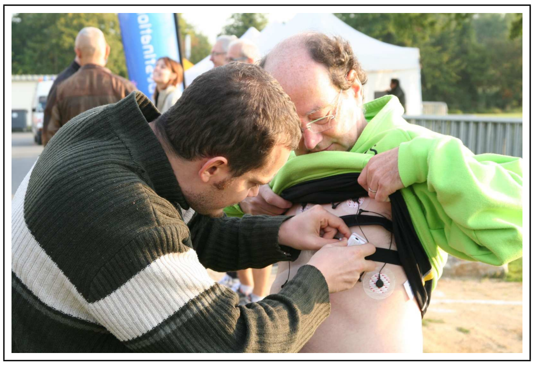

Figure 3: One volunteer is equipped with an ECG-enabled SHIMMER sensor for the running race at Ker Lann campus

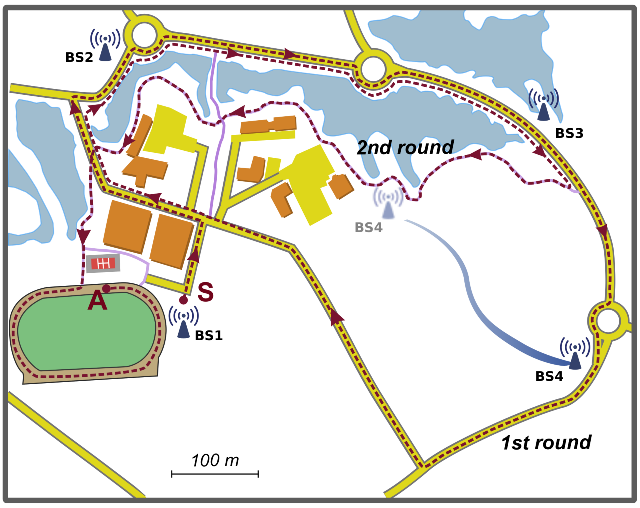

Figure 4: Running route and location of base stations during the 3.9 km running race at Ker Lann campus

5. FIELD TRIALS DURING AN INTRA-CAMPUS SPORTS EVENT

5.1 Trials conditions

The preliminary experiments mentioned in Section 4 gave us a crude idea of what can be expected from sensors and base stations in a marathon scenario, but we decided to get a proof-of-concept in more realistic conditions. Field trials were conducted during an intra-campus sports event that occurred in September 2011 on the Ker Lann campus (France). A 3.9 km running race was organized during that event, and three volunteers (two students and a professor) were equipped with ECG-enabled SHIMMER sensors on that occasion (see Fig. 3). Four base stations (BS1 to BS4) were deployed along the running route (Fig. 4). This route was a loop, so the runners passed two times near each base station. BS4 had to be moved between the first and second round, since the second round was shorter than the first round. The distance between successive base stations was about 500 meters.

During these field trials at Ker Lann campus each base

Figure 5: One base station (i.e. netbook + TELOS-B mote) installed on the roadside during the running race at Ker Lann campus

station was composed of a netbook connected to a TELOS-B mote (see Fig. 5). The netbooks were not connected to a remote monitoring center on that occasion, since our motivation was primarily to observe how ECG data could be collected from the SHIMMER sensors as the runners passed close to a base station. Each base station therefore simply recorded the data obtained from passing sensors in flash memory, and the data recorded by all four base stations were reassembled and analyzed after the race was over.

5.2 Protocol for data acquisition and transmission

We developed specific code in nesC in order to ensure the acquisition, storage, and transmission of data between SHIMMER sensors and TELOS-B platforms. The main features of this code are detailed below.

Data acquisition on a SHIMMER sensor.

The acquisition of ECG data on each SHIMMER sensor is performed on the two 12-bit channels (RA-LL and LA-LL leads), with 500 Hz sampling frequency. The 12 kbps data stream hence produced is compressed on-the-fly, using a simple differential compression algorithm that lowers the bitrate to about 6 kbps. The data stream is then packetized in small bundles, each bundle containing a 34-byte header (including the sensor's identifier and a local timestamp), and 80 bytes of compressed ECG data. A bundle can thus fit in a single 802.15.4 data frame (whose size cannot exceed 128 bytes). After its creation a bundle is stored as a file in the SHIMMER sensor's micro-SD card, from which it can be retrieved to be transmitted during radio contacts with a base station.

Data transmission between SHIMMER sensor and base station.

Since each base station (using a TELOS-B mote as an 802.15.4 transceiver) can have to interact with several passing SHIMMER sensors at the same time, some form of medium access control is required in order to avoid frame collisions on the radio channel. We therefore designed and implemented a simple coordination protocol, whereby a base station can allocate time slots to each sensor in range for data transmissions. This protocol is strongly inspired from the GTS (Guaranteed Time Slot) allocation method defined in the ZigBee specification [7]. Each base station periodically broadcasts a beacon frame, which allows neighbor SHIMMER sensors to detect its presence. The interval between two successive beacons is split in two parts: a Contention Access Period (CAP), and a Contention-Free Period (CFP). During the CAP sensors can notify the base station of their presence and request the allocation of a time slot for data transmission. During the CFP each sensor can use its allocated time slot to upload bundles of data to the base station, with no interference from other sensors. Since all sensors do not necessarily have the same amount of data (that is, the same number of data bundles) to upload to the base station, the number of available data bundles is included in the request a sensor sends to the base station during the CAP. The base station can thus adjust the duration of the CAP time slots assigned to neighbor sensors proportionally to the amount of data they need to upload. Information about the allocation, ordering and duration of time slots is notified to all neighbor sensors at once, using a single frame that is broadcast by the base station at the end of the CAP and just before the CFP.

Each bundle of ECG data can fit in a single data frame, so no fragmentation is required. MAC-level data frame acknowledgement is enabled during the CFP: after sending a data bundle a sensor receives an ACK frame, that confirms that the data bundle has been received and accepted by the base station. If the ACK frame is not received the same data frame is sent again after a timeout. Upon receiving an ACK for a data frame the corresponding bundle remains in the micro-SD filesystem, but it is tagged as "transmitted" so the sensor will not try to upload this bundle again (to the same base station or to the next one).

Several strategies can be devised in order to determine which data bundles should be sent first when a SHIMMER sensor establishes a connection with a nearby base station. An option is for example to preserve the chronological ordering of data bundles, uploading the oldest bundles first. For the field trials we decided to favor the transmission of "fresh" ECG data first, and to fill the gaps by uploading older bundles whenever possible. The transmission algorithm running on the sensors was therefore implemented in such a way that "real-time" bundles (i.e. those produced during a radio contact between sensor and base station) were uploaded to the base station first, and the time remaining during each GTS time slot was used to upload "old" bundles (i.e. bundles that had been stored on the sensor's micro-SD card, and that had not been uploaded to a base station yet). A monitoring system receiving ECG data from a marathon runner could thus display the current heart activity of the runner, and optionally allow a user to rewind the ECG stream in order to display past events.

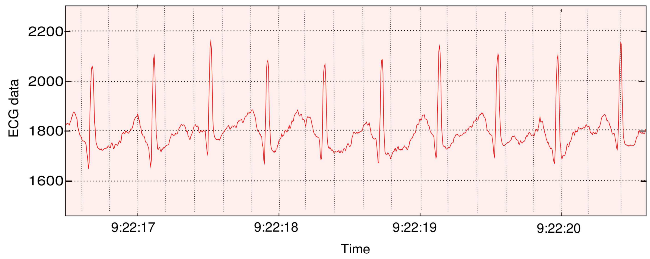

Figure 6: Example of ECG data collected from a runner's sensor during the race

Data collection on a base station.

Besides serving as a coordinator for wireless medium access, the base station receives ECG data bundles from passing sensors. As mentioned before, each bundle includes an identifier of the source sensor and a timestamp that is associated with the data when they are packetized. The SHIMMER platform does not include any real-time clock, so timestamping is performed based on a local timer that ticks every 100 ms. When a data bundle is sent by a sensor to a nearby base station, the duration since this bundle was recorded is calculated, and this duration is inserted in the bundle's header in place of the record time. When the data frame is received by the base station the actual time of the bundle's production is calculated based on the current time (according to the base station's system clock), on the duration specified in the bundle's header, and on an estimation of the time required to transmit the data frame between sensor and base station (this transmission can be estimated quite accurately since data frames are transmitted during a CFP period, when no backoff mechanism is used).

Every bundle of ECG data thus received by a base station contains an indication of where and when it was produced. Each base station can therefore record data bundles for deferred analysis, or transmit these bundles to a remote site with no risk of data mixup or disordering.

5.3 Results

During the field trials at Ker Lann campus the three runners covered the 3.9 kilometers in about 22 minutes, and each sensor produced about 2.5 MB of ECG data (that is, about 65.000 compressed bundles) during that time.

Figure 6 shows an excerpt of the ECG data stream that was collected from one of the sensors during the race. This data stream would probably need some noise reduction processing, but as such it is exploitable by a cardiologist.

During the race our prime motivation was to observe if the data bundles produced continuously on each sensor could actually be transmitted when the sensor established radio contact with one or another base station. Figure 7 shows the timeline of transmissions between the three sensors (S1 to S3) and the four base stations (BS-1 to BS-4). More precisely it shows the duration of the radio contacts as each sensor passed close to a base station (dotted lines), and the amount of data that were uploaded to the base station during that contact. For example, a radio contact was established between S1 and BS-1 between 09h15m55s and 09h16m22s. It can be observed that during this 27-second contact only a small amount of data was uploaded from S1 to BS-1, and none of the data acquired before the radio contact was uploaded to BS-1. About two minutes later S1 established a radio contact with BS-2, and during this contact 82% of the data produced since the former contact was uploaded to BS-2. The next contact was established between S1 and BS-3, and this time S1 managed to upload to BS-3 all the data it had produced since its contact with BS-2, plus 17% of the data that it had failed to transmit to BS-2.

By observing carefully the timing of the radio contacts between the sensors and base stations, it can be observed that the data uploading process was more effective when a base station only had to interact with one or two sensors simultaneously. In contrast, when a sensor had to deal with the three sensors (as happened at the beginning of the race when all three sensors passed close to BS-1 at the same time) only a fraction of the data could be uploaded to the BS.

During the race the duration of radio contacts ranged between 11 seconds and 48 seconds, with an average value of 19 seconds. During these contacts the sensors managed to upload 79% of their data to the base stations. The remaining 21% of data bundles were not lost, though, since they were stored on each sensor's micro-SD card and could be collected after the race.

6. DISCUSSION

6.1 Lessons learned from the field trials

Globally the results of the field trials confirm that the protocol we implemented can indeed tolerate transient connectivity between sensors and base stations, and is resilient to connectivity disruptions. However they also show that in spite of this disruption-tolerant procotol not all data acquired during the race could be uploaded to the base stations.

A major outcome of these field trials is that they clearly show the limits of outdoor ECG data acquisition using short-range, low-rate transmissions based on 802.15.4 transceivers. Although these field trials were conducted with only three sensors, and although the distance between successive base stations was rather short (about 400 meters instead of the 1 or 2 km required during a marathon race), only a fraction of the data acquired on each sensor could be collected by base stations during the race.

Of course the amount of data produced on each sensor could certainly be reduced, as explained in Section 4, by adjusting the frequency and resolution of ECG acquisition. A more efficient compression algorithm could also be implemented, provided the code of this algorithm could hold in the SHIMMER platform's 48 kB flash memory. Our current code (which handles data acquisition, compression, packetization, storage, and transmissions) has a 45 kB footprint. Replacing the simple differential compression algorithm it contains by a more efficient compression algorithm without exceeding the SHIMMER's capacity would be quite a challenge.

6.2 Ongoing and future work

In order to get around the constraints mentioned above, we started investigating an alternative approach whereby smartphones carried by runners can serve as relays between SHIMMER sensors and base stations. In this new configuration the ECG data stream produced by a SHIMMER sensor is transmitted directly and continuously to a smartphone through a Bluetooth RFCOMM link. The smartphone processes this data stream (packetization + compression + storage + optional signal analysis), and the upload of data bundles from a smartphone to roadside base stations can be performed using Wi-Fi wireless links rather than 802.15.4 links. Base stations are then standard Wi-Fi access points, with broadband connectivity to the monitoring center. This approach is expected to raise the limitations we observed with 802.15.4 transmissions. Indeed, with Wi-Fi transceivers instead of 802.15.4 transceivers the range of wireless transmissions is increased by approximately one order of magnitude, and the data throughput is increased by about two orders of magnitude. Optionally, data bundles can also be transmitted from a smartphone directly to a remote monitoring center, using 3G (UMTS or CDMA2000) connections for data transmission.

One of the drawbacks of this alternative approach is of course that runners might be reluctant to carry a smartphone in an armband, in addition to the SHIMMER sensor. A SHIMMER unit with its ECG expansion module weighs about 22 grams. In contrast a smartphone usually weighs between 150 and 200 grams. Additionally, the autonomy of a smartphone might be an issue during a marathon race. Experiments conducted in our laboratory show that an Android smartphone maintaining one Bluetooth connection with a SHIMMER sensor and one Wi-Fi connection with a nearby access point can deplete its battery in a couple of hours. The situation is even worse if a UMTS connection is used instead of Wi-Fi to upload data bundles to a remote site. Further experiments are planned in order to check if a smartphone can run continuously (with continuous Bluetooth transmissions and sporadic Wi-Fi or 3G transmissions) during the duration of a marathon race.

7. CONCLUSION

Off-the-shelf wireless sensing devices such as the SHIMMER platform open a wide range of perspectives for health monitoring. Yet because of the limited computation and transmission capacities of such platforms most applications considered to date imply either indoor real-time data streaming, or ambulatory data recording. With disruption-tolerant networking another approach can be considered, whereby data are captured and stored continuously on the sensor platform, and transient connectivity with one or several base stations is used opportunistically to upload data to a remote monitoring center.

In order to illustrate this approach we investigate a challenging scenario: the ECG monitoring of runners during a marathon race. Preliminary field trials have been conducted during a campus sports event, using SHIMMER platforms for data acquisition and IEEE 802.15.4 transmissions to upload ECG data to roadside base stations. These trials confirm that capturing and transmitting ECG data during a running race is indeed feasible, but that this application is hampered by the low computation power, short transmission range, and low transmission bitrate offered by SHIMMER sensors. Work is now in progress in order to use Android smartphones as relays between ECG sensors and roadside base stations. With this approach each runner must carry a smartphone, additionally to the ECG sensor. ECG data are received and processed continuously by the smartphone

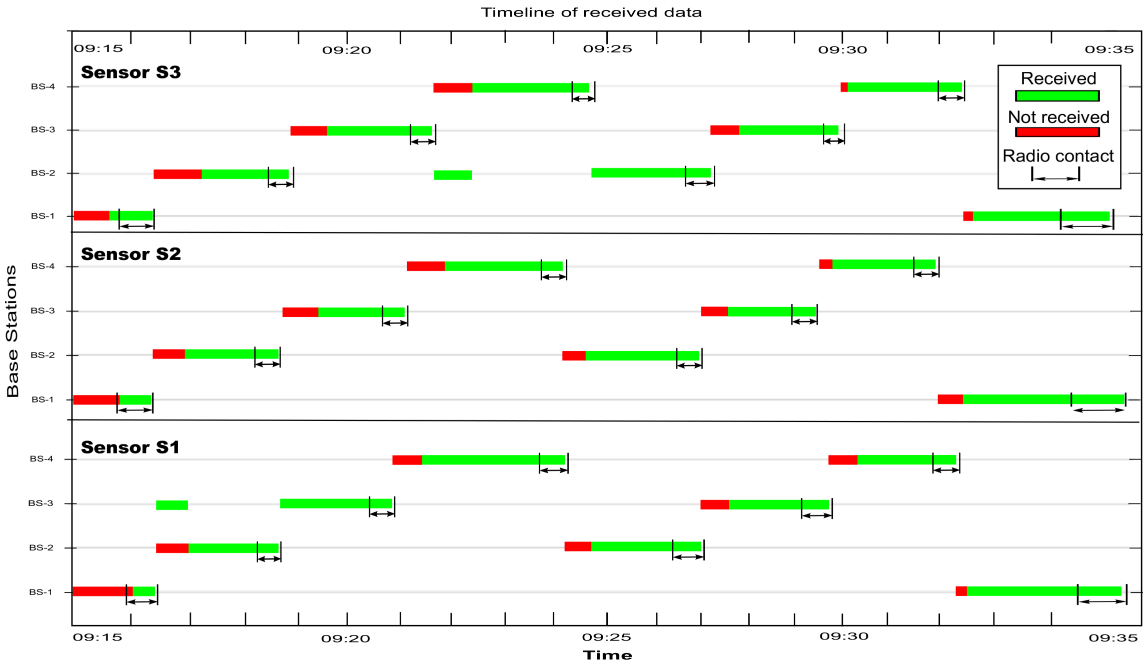

Figure 7: Timeline of data transmissions during the race for the three sensors

through a Bluetooth RFCOMM link. The smartphone can then upload data bundles sporadically to Wi-Fi access points placed on the roadside, or directly to a remote monitoring site through a 3G connection.

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